

January, 1995

LBL-36740

DISORIENTED CHIRAL CONDENSATE*ZHENG HUANG[†]

*Theoretical Physics Group, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720, USA
E-mail: huang@theorm.lbl.gov*

ABSTRACT

The current theoretical understanding of disoriented chiral condensate is briefly reviewed. I discuss the basic idea, the formation mechanism and experimental signatures of DCC in high energy collisions.

1. Basic Idea

The spontaneous symmetry-breaking mechanism plays a very important role in high energy physics. It is known that there are at least two occurrences of such phenomenon at work in the standard model: the electroweak symmetry-breaking and the chiral symmetry-breaking, in which the observed asymmetries are attributed entirely to the vacuum states of our universe. But how do we test this idea directly? Is there any way that we can create a suitable condition under which the vacuum state is disturbed for a small region of space-time so that we may be able to observe some quite different excitations and domain structures in the vacuum?

Let us examine the possibility for the chiral symmetry in strong interactions. Suppose a very high energy proton-proton or nucleus-nucleus collision in cosmic rays or in Tevatron or RHIC collider. Occasionally, the collision creates a large number of low energy (small p_t) particles, mainly pions. These strongly interacting particles initially populate in a small phase space and rescatter many times before leaving the system, heating up a small local space-time region Ω . The initial fluctuations may or may not reach a thermal equilibrium. Outside Ω , it is the normal vacuum state. The pressure difference between the interior and the exterior caused by the initial fluctuations results in a rapid expansion, especially in the beam direction. The evolution of the fluctuations involves a rolling down from the top of potential to the “valley” of the potential, governed mainly by the classical equation of motion. Such a “rolling-down” may be unstable for long wavelength modes, which will be exponentially amplified. The domains of different vacuum structure may emerge in the interior, leading to a quite different characteristic of the pion productions when

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Divisions of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and by the Natural Sciences and Engineering Research Council of Canada.

[†]Talk presented at the Beyond The Standard Model IV, 13-18 December 1994, Lake Tahoe, California

these domains decay. The formation of “disoriented” domains is referred to as the “disoriented chiral condensate (DCC)”¹.

2. Formation Mechanism

2.1. The Model

How do we tackle the problem at hand since the system contains strongly interacting particles and the standard perturbation theory fails? Fortunately, we are only dealing with low energy hadrons, there is a very powerful effective theory of QCD at low energy, that is, the σ -model. There are two versions of the σ -model: the linear model and the non-linear model. They are shown to be equivalent to each other at low energy, i.e. both of them satisfy the low energy theorem², which is uniquely determined by the symmetry ($O(4)$). We would like to also include the oscillation effects between the σ field and pion fields. Therefore, the linear σ -model is more appropriate as long as we confine ourself to the low energy modes. The scalar potential looks like a Higgs potential in the electroweak standard model except for a very large self-coupling λ . Remember, however, that a perturbative series corresponds to a momentum expansion, which is well justified when the energy is small compared to $4\pi f_\pi \sim 1$ GeV. For example, the partial wave amplitudes for $\pi\pi$ scatterings, given by the low energy theorem, are

$$a_{00} = \frac{s}{16\pi^2 f_\pi^2} \quad , \quad a_{11} = \frac{s}{96\pi^2 f_\pi^2} \quad , \quad a_{20} = -\frac{s}{32\pi^2 f_\pi^2} \quad (1)$$

which are clearly λ -independent.

Therefore, as long as the energy of σ and π 's is small, we can ignore the quantum loop effects and treat the system as classical (However, it is argued that the quantum effects can be important in the early evolution of the system before σ and π 's decouple from each other³). As the system expands, the typical energy-momentum becomes even smaller, the evolution of the system is thus governed by the classical equations of motion. However, we should point out that an initial low energy configuration is our starting point. We have not started from scratch and calculated the cross section, e.g., $\sigma(pp \rightarrow 10^3 \pi$'s, $p_t < 200$ MeV) which necessarily involves quantum processes. It is only the fact that most particles created in a given event are dominantly soft pions in hadron-hadron collisions. In a real experiment, the condition of a low energy is guaranteed by a physical p_t cut from above ($p_t < 200$ MeV). In most of theoretical simulations, such condition is automatically met by choosing a lattice spacing $a \sim 1$

fm.

2.2. Equations of Motion

We now have a well-defined problem: given an initial condition, solving the classical equations of motion. In the standard linear σ -model, the equations of motion are given by,

$$\square\phi = \lambda(f_\pi^2 - \phi^2)\phi + Hn_\sigma, \quad (2)$$

where $\phi \equiv (\sigma, \boldsymbol{\pi})$ is a vector in internal space, $n_\sigma = (1, \mathbf{0})$, and Hn_σ is an explicit chiral symmetry breaking term due to finite quark masses. Our goal is to solve Eq. (2).

What kind of initial conditions that one may choose? The most general ones are random gaussian distributions allowed by a typical energy density or temperature (just like in the chaotic inflation in the early universe), where the scalar fields take on different values in different regions in Ω . To specify a gaussian form, one has to choose a mean value $\langle\phi\rangle$ over the spatial volume of Ω and a magnitude of the fluctuations $\delta\phi^2$. Let us separate ϕ into two parts

$$\phi = \langle\phi\rangle + \delta\phi, \quad (3)$$

where by definition $\langle\delta\phi\rangle = 0$. The averaged scalar potential is

$$\langle V \rangle = \frac{\lambda}{4}(\langle\phi\rangle^2 + \langle\delta\phi^2\rangle - f_\pi^2)^2 - H\langle\sigma\rangle. \quad (4)$$

If $\langle\delta\phi^2\rangle$ is to be replaced by a thermal fluctuation where $\langle\delta\phi^2\rangle = T^2/4$, one recovers the well-known one loop effective potential at finite temperature. The instability occurs whenever $\langle\phi\rangle^2 + \langle\delta\phi^2\rangle - f_\pi^2 < 0$.

2.3. Initial Fluctuations

The existence of $\langle\delta\phi^2\rangle$ renders the effective potential for the mean field $\langle\phi\rangle$ different from a zero temperature one. $\langle\delta\phi^2\rangle - f_\pi^2$ determines the temporal shape of the potential. There are two scenarios to generate an unstable “rolling-down”. In an “annealing” scenario⁴, the system is assumed to be in a thermal equilibrium, at least initially. The initial value of $\langle\phi\rangle$ has to match with the equilibrium position (the minimum) of the potential determined by initial value of $\langle\delta\phi^2\rangle$. For example, if initially $\langle\delta\phi^2\rangle - f_\pi^2 > 0$, the chiral symmetry is restored, then the initial value $\langle\phi\rangle \simeq 0$ (approximately due to the explicit symmetry-breaking). The rolling-down is generated as the system expands, the $\langle\delta\phi^2\rangle$ decreases and thus the equilibrium position changes. Such a situation is best realized in a first order phase transition when the minimum changes discontinuously and when the potential is sufficiently flat. In the

problem we have here, it seems difficult to achieve a sufficient rolling-down time in the annealing case.

The second scenario is the “quenching” mechanism⁵ which does not have much to do with the phase transition. There is no thermal equilibrium at the initial stage, the mean field $\langle\phi\rangle$ is displaced from the minimum of the potential and rolls down to the valley. As long as $|\langle\phi\rangle|$ is smaller than $|\langle\phi_{\text{eq}}\rangle|$ at which the effective potential is minimized, the instability develops and the long wavelength modes are exponentially amplified. The expansion causes the fluctuations to decrease, which tends to increase the roll-down time. It is clear that such a situation will not be possible if the fluctuations $\langle\delta\phi^2\rangle > f_\pi^2$ which renders the chiral symmetry restore and $|\langle\phi_{\text{eq}}\rangle| = 0$. The system has to be cool enough in order for quenching at work. A numerical simulation shows that domain structure is most prominent in the quenching case⁶.

2.4. Numerical Simulations

Numerical simulations have been done extensively in the literatures⁷. Usually the lattice spacing is chosen to be 0.5~1.0 fm, which cuts off the momenta above 200~400 MeV, appropriate for studying soft pion modes. In many cases, a boost invariance in the longitudinal direction is assumed so that the longitudinal expansion is automatically included. To monitor the domain formation, one has to compute the two point correlation function. Figure 1 shows the evolution of an initially random noise with the proper time τ using a quenching initial condition⁶. At $\tau = 5$ fm, some domain structure clearly emerges. The typical domain size can be as large as 2~3 fm in the transverse dimension and 1~2 unit in rapidity distribution.

3. Signals of DCC

3.1. Anomalous Isospin Fluctuation

The existence of the domain structure of the pion fields can be most effectively observed in the phase space distribution of pion multiplicity when the “disorientation” of individual domain is radiated away in Goldstone modes (pions). The simplest way to quantize the semiclassical field and to describe its decay is given in terms of a coherent state

$$|\phi_{\text{cl}}\rangle = N \exp \left\{ \int d^3k \phi_{\text{cl}}(k) a^\dagger(k) \right\} |0\rangle. \quad (5)$$

There are some subtle issues on the conservation of quantum numbers in a coherent state, while a squeezed state⁸ seems to be more consistent in many ways. Such coherent emission of semiclassical pion field would lead to some unusual fluctuations in a given lego plot acceptance sector $\Delta y \Delta\phi$. One may look for some unusually

Fig. 1. This is what a DCC may look like! The top one is the initial random configuration, the bottom one is the profile of the field at $\tau = 5$ fm where two domains are clearly visible. A quenching initial condition is used.

rich or poor neutral pions compared to the charged pions in the given sector. The Centauro and anti-Centauro events in the cosmic ray experiments may well be a possible candidate for such signal. If the interaction volume is small so that it contains only one such domain as it may be the case in pp collisions, it may be possible to count event-to-event the ratio (f) of neutral to total pions yield. If all orientations in a domain are equally possible, a simple calculation shows ¹ that the probability distribution (n) is $\frac{1}{n} \frac{dn}{df} = \frac{1}{2\sqrt{f}}$, very different from the normal binomial distribution. This is what the T864 test/experiment at Tevatron led by Bjorken and Taylor is currently looking for. To further reduce the background, one may also apply a p_t cut from above (say, 200 MeV) since after all the domain size should be ≥ 1 fm to be of any interest.

The theoretical simulation indicates that under suitable initial conditions, preferably the quenching conditions, the formation of sizable domains is quite possible. In a real experiment, the signal will be diluted by the measure of the probability for such conditions in all possible conditions and the irreducible backgrounds. Therefore, the production of DCC may merely be a rare event. Some accumulation of statistics may be needed. The odds that the formation of domain favors a non-equilibrium condition seems to suggest that a pp or $p\bar{p}$ collision has a better chance than a heavy nucleus collision. Currently, there has been no realistic simulation on the cross section for the DCC production for the Tevatron Minimax project.

3.2. Measuring Domain Size

It is also very important to measure the size of domain which would reveal the existence of a domain structure independently. The simplest way is to look at the pion multiplicity as a function of p_t . For example, if the typical domain size is 2 fm, we should observe a rise of the multiplicity when p_t drops through ~ 100 MeV.

3.3. $\rho/\omega \rightarrow \ell^+\ell^-$ Decays

It has been suggested ⁹ that when the hadronic resonances decay inside the DCC, their electromagnetic decay modes show a clear signal of the disorientation of the background, serving as an alternative signature of DCC. The idea is to use the fact that electromagnetic interactions break the chiral symmetry explicitly (even in the chiral limit). The simplest way to see this is that the u and the d quarks have different electric charges, and as a result, π^+ and π^0 have different masses.

In the normal vacuum, the QCD vacuum aligns with the direction of electromagnetic interactions. However, the DCC does not in general align with the EM interactions. One immediate consequence of this misalignment is that the vector-meson dominance no longer holds for the EM current in the familiar way. In the disoriented domain, the meson state to which the isovector current couples is no longer a single

meson state of mass 770 MeV but a linear combination of all possible charge states with mass 770 MeV and 1260 MeV ($= m_{a_1}$). If all possible orientations of the chiral $SU(2)_L \times SU(2)_R$ are allowed with an equal probability, on average, all six transitions, $\rho \rightarrow \gamma$ and $a_1 \rightarrow \gamma$, occur with an equal probability 1/6. This means that the ρ peak in the $\ell^+ \ell^-$ mass plot will be reduced by half if all three charge states of ρ are produced with an equal rate, and a new broad bump of width $\simeq 300$ MeV ($= \Gamma_{a_1}$) may appear at 1260 MeV

$$\Gamma(\rho(770\text{MeV}) \rightarrow \ell^+ \ell^-)_{\text{DCC}} = \frac{1}{2} \Gamma(\rho^0 \rightarrow \ell^+ \ell^-)_{\text{normal}} , \quad (6)$$

$$\Gamma(a_1(1260\text{MeV}) \rightarrow \ell^+ \ell^-)_{\text{DCC}} = \left(\frac{m_\rho}{m_{a_1}} \right)^3 \Gamma(\rho(770\text{MeV}) \rightarrow \ell^+ \ell^-)_{\text{DCC}} \quad (7)$$

This prediction is little affected by the current quark mass. It is a consequence of the misalignment of the DCC with the electroweak vacuum fixed by the Higgs field, so it would disappear only at $F_\pi \rightarrow 0$ in which a distinction between the ρ and the a_1 ceases to be meaningful.

In contrast, the isoscalar current is dominated by the ω meson (780 MeV) and the ϕ meson (1020 MeV) in the normal vacuum, which are the two singlets $(\mathbf{1}, \mathbf{1})$ of $SU(2)_L \times SU(2)_R$. Therefore, no matter how much the DCC vacuum is chirally disoriented, the ω and ϕ mesons are not affected at all. In addition, because of its short lifetime, the ρ decays mostly inside the DCC domain while the ω lifetime is probably too long for it to decay inside the DCC domain. Therefore there is a chance to test the formation of the DCC by carefully measuring the dilepton decays of the ρ and the ω mesons.

4. What We (Hope to) Learn

We believe that if the idea of spontaneous symmetry-breaking is correct, the vacuum is a quite complicated object. For a continuous symmetry, there exist infinitely many degenerate (or almost degenerate) vacua. The fact that we only live in one of them does not exclude us from being aware of others. We know that there are Goldstone modes excited long the directions of degeneracy. Pions are indeed very light. Another possibility is to disturb the vacuum by a high energy collision, where we are not using the high energy frontier to produce a top quark pair, rather, converting the energy into large entropy, i.e. producing many many low energy particles. These collision debris are distributed over a extended spatial region, interacting with the vacuum using their long wavelength modes. Some of these modes may be unstable and tend to grow exponentially, leading to the domains of different orientations in this excited region.

This new phenomenon is called “the vacuum engineering” by T.D. Lee¹⁰. A more concrete picture known as “Baked Alaska” has been suggested by Bjorken et al. who

speculates that a cool interior of large “fireball” may indeed be produced in very high energy collisions. In addition to the Minimax project, there have been some experimental initiatives searching for DCC at upcoming RHIC. This will open up not only an opportunity for studying the low energy multiparticle physics in extremely high energy collisions, but also a window for a direct test of the idea of spontaneous symmetry-breaking. On this hopeful note, let me stop.

5. Acknowledgements

I wish to thank M. Asakawa, M. Suzuki and X.-N. Wang for their fruitful collaborations. I am grateful to J. Bjorken and Y. Kluger for many conversations on this subject. This work was supported by the Director, Office of Energy Research, Office of High Energy, Division of High Energy Physics of the U.S. Department of Energy under contract DE-AC03-76SF00098 and the National Science and Engineering Research Council of Canada.

6. References

1. A. A. Anselm and M. G. Ryskin, Phys. Lett. B **266**, 482 (1991); J. -P. Blaizot and A. Krzywcki, Phys. Rev. D **46**, 246 (1992); J. D. Bjorken, K. L. Kowalski, and C. C. Taylor, SLAC preprint SLAC-PUB-6109.
2. S. Weinberg, Phys. Rev. Lett. **17**, 616 (1966).
3. F. Cooper, Y. Kluger, E. Mottola, and J. P. Paz, Los Alamos preprint (1994), hep-ph/9404357.
4. S. Gavin and B. Müller, Phys. Lett. **B329**, 486 (1994).
5. K. Rajagopal and F. Wilczek, Nucl. Phys. **B404**, 577 (1993).
6. M. Asakawa, Z. Huang, and X.-N. Wang, LBL preprint LBL-35981, to appear in Phys. Rev. Lett.
7. Z. Huang, Phys. Rev. **D49**, 16 (1994); Z. Huang and X.-N. Wang, Phys. Rev. D **49**, R4339 (1994); S. Gavin, A. Gocksch, and R. D. Pisarski, Phys. Rev. Lett. **72**, 2143 (1994); D. Boyanovsky, H. J. de Vega, and R. Holman, University of Pittsburgh preprint PITT-94-01, hep-ph/9401303; T. Cohen, M. Banerjee, M. Nielsen and X. Jin, Phys. Lett. **B333**, 166 (1994).
8. R. Amado and I. Kogan, Princeton Preprint PUPT-1483, hep-ph/9407252.
9. Z. Huang, M. Suzuki and X.-N. Wang, Phys. Rev. **D50**, 2277 (1994)
10. T.D. Lee, in *Particle Physics and Introduction to Field Theory*, Harwood Academic Publishers, New York, 1981.

This figure "fig1-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9501366v1>